

Tau Neutrinos from Astrophysical and Cosmological Sources

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Abstract. Previous work on the neutrino spectra from high energy sources has not included the tau neutrinos directly produced by the decays in the source. Here we consider the tau neutrino component and discuss how its inclusion modifies the expected neutrino spectra. We discuss implications for interpreting any observed tau neutrino component in TeV - UHE events as evidence of $\nu_\mu \rightarrow \nu_\tau$ oscillations.

1 Introduction

The observation of high energy neutrinos from beyond Earth will open a new window on astrophysics and cosmology. Presently much effort is being expended on designing and deploying detectors and methodologies capable of resolving the flavour of the incoming neutrino flux. One motivation for doing this is that the absolute sensitivity, or relative sensitivity compared with background, may be significantly greater for one neutrino species than the other species (Dutta et al., 2000). Another primary motivation for identifying the neutrino flavour is to test the hypothesis that neutrinos undergo flavour oscillation as they propagate from source to Earth. Indeed a number of atmospheric, accelerator and solar neutrino experiments hint at the existence of neutrino oscillations, although the experiments are not yet sufficiently consistent to delineate a unique solution (Akhmedov, 2000). The most favoured solution, fitting the latest SuperKamiokande data, involves $\nu_\mu \rightarrow \nu_\tau$ oscillation with a mass difference of $\Delta m_\nu^2 \sim 10^{-3} \text{eV}^2$. Because the non-oscillation production of ν_τ is assumed to be negligible relative to ν_e and ν_μ production, and the cascade ν_τ produced by collisions of primary ν_e and ν_μ flux with the relic cosmic neutrino background is orders of magnitude less than the primary ν_e and ν_μ flux, any detected ν_τ component from a source outside the Solar System is currently expected to be indicative of oscillation.

In this paper, we briefly report some results of our investigation into high energy ν_τ production, presented elsewhere

(MacGibbon et al., 2001). We illustrate that the ν_τ component at the high energy end in the hadronic decays is significantly higher than previously assumed and that this can have observational consequences.

2 Neutrino Production

A number of sources for TeV-UHE neutrinos have been postulated: for example active galactic nuclei (AGN) (Athar et al., 2000; Husain, 2000); topological defects such as superconducting, ordinary or VHS cosmic strings (Bhattacharjee and Sigl, 2000; Hill et al., 1987; Wichoski et al., 1998); supermassive gauge and scalar particle (X particle) decay or annihilation (Albuquerque et al., 2000); and Hawking evaporation of primordial black holes (MacGibbon and Carr, 1991; MacGibbon and Webber, 1990; Halzen et al., 1995). In all of these scenarios, the final state particle distributions are expected to be dominated by hadronic decays at the source. In these decays over 90% of the final state emission will be π^0 , π^+ , and π^- , with the remainder mainly nucleons which decay into protons and antiprotons. On astrophysical timescales, the π^\pm decay into ν_e and ν_μ and e^\pm . It is known that the final cluster states (pions and nucleons) in QCD jets at accelerator energies are well described by the fragmentation function

$$\frac{dN}{dx} = \frac{15}{16} x^{-3/2} (1-x)^2, \quad (1)$$

where $x = E/m_J$ and m_J is the total energy of the decaying jet (Hill et al., 1987). This distribution continues down to $E \sim 1 \text{ GeV}$. When convolved with the π^\pm decay, Eq.(1) leads to, similarly, a dominant $E^{-3/2}$ term in the ν_e and ν_μ spectra at $x \lesssim 0.1$ and $dN_{\nu_e, \nu_\mu}/dE \rightarrow 0$ as $x \rightarrow 1$. (For a full derivation of the ν_e and ν_μ spectra using fragmentation function (1) see (Wichoski et al., 1998).)

The production channels for the ν_τ , however, are substantially different. The tau neutrinos are only produced in significant numbers once the tau lepton and heavy quark masses,

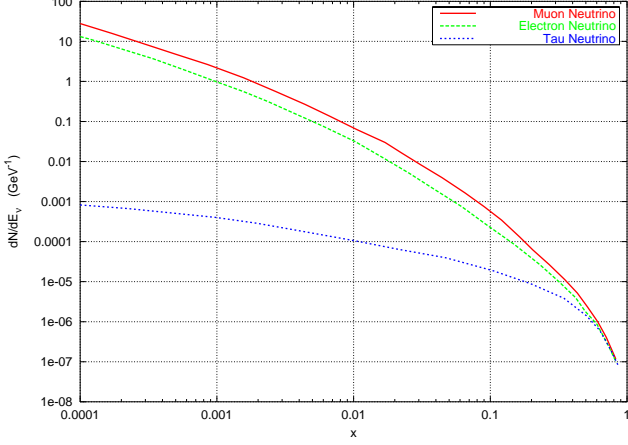


Fig. 1. The neutrino spectra, dN/dE vs $x = E/m_J$, generated by the decay of $m_J = 10$ TeV $q\bar{q}$ jets. The solid line represents ν_μ , the dashed line represents ν_e , and the dotted line represents ν_τ .

$m_\tau = 1.78$ GeV, $m_b \sim 4$ GeV, $m_t \sim 174$ GeV, are surpassed. The greatest contribution comes from the t quark decay. Because ν_τ production is suppressed compared with other species, it has been assumed in flux calculations that the ν_τ spectrum is orders of magnitude less than the ν_e and ν_μ spectra at all x . This is not so. While indeed the total number of ν_τ produced per jet is less than 10^{-3} of the total number of ν_e and ν_μ , the high x tau neutrinos are predominantly produced by the initial decays of the heavier quarks with shorter lifetimes and the ν_e and ν_μ are produced by the final state cluster decays of the much lighter pions. This leads to significantly greater relative contribution from ν_τ at high x than previously assumed. The fragmentation distribution (1) is no longer relevant for the tau neutrino.

In Fig.(1) we show the ν_τ spectrum, together with the ν_e and ν_μ spectra, generated by the decay of 10 TeV $q\bar{q}$ jets. To simulate these spectra we used the QCD event generator HERWIG (Corcella et al., 2001) and the process $e^+e^- \rightarrow q_i\bar{q}_i$ (g), $i = \text{all } q \text{ flavours}$. Consistent spectra are obtained with PYTHIA/JETSET (see MacGibbon et al. (2001)). Note that in the region $0.1 \lesssim x \lesssim 1$, the tau neutrinos make up more than one tenth of the total neutrino contribution. We also note that below $x \lesssim 0.1$, dN_{ν_τ}/dE falls off with roughly an $E^{-1/2}$ slope, and not the $E^{-3/2}$ slope of the ν_e and ν_μ spectra. Because the 1 GeV - UHE cosmic ray flux backgrounds are expected to fall off as $dN/dE \propto E^{-y}$ where $2 < y < 3$, we also plot $E^2 dN/dE$ in Fig.(2).

From our 300 GeV - 75 TeV simulations, we find that the ν_τ spectrum generated by $q\bar{q}$ jet decay can be parametrized as

$$\frac{dN_{\nu_\tau}}{dE_{\nu_\tau}} \simeq \left(\frac{1}{2m_J} \right) \left[0.15 \left(\frac{E_{\nu_\tau}}{m_J} \right)^{-1/2} - 0.36 + 0.27 \left(\frac{E_{\nu_\tau}}{m_J} \right)^{1/2} - 0.06 \left(\frac{E_{\nu_\tau}}{m_J} \right)^{3/2} \right], \quad (2)$$

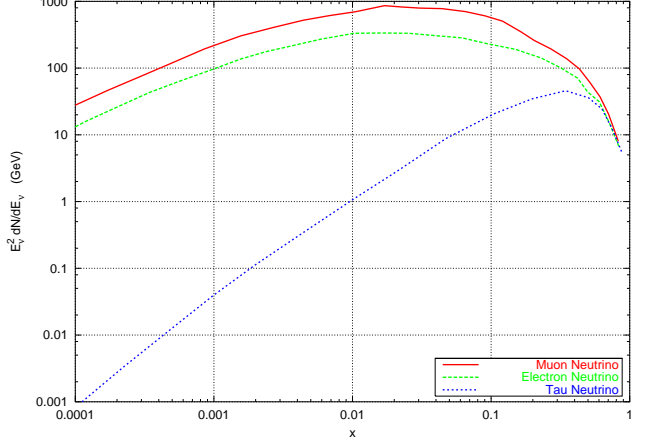


Fig. 2. The $E^2 dN/dE$ vs $x = E/m_J$ neutrino spectra for the same jet decay as in Fig.(1).

per jet. Similarly the number (multiplicity) of neutrinos produced per $q\bar{q}$ jet and the average neutrino energy scale as

$$N_{\nu_\tau} \simeq 0.035 \left(\frac{m_J}{\text{GeV}} \right)^{0.03}, \quad \bar{E}_{\nu_\tau} \simeq 0.2 \left(\frac{m_J}{\text{GeV}} \right)^{0.9} \text{ GeV}, \quad (3)$$

$$N_{\nu_e} \simeq 2.0 \left(\frac{m_J}{\text{GeV}} \right)^{0.3}, \quad \bar{E}_{\nu_e} \simeq 0.04 \left(\frac{m_J}{\text{GeV}} \right)^{0.7} \text{ GeV}, \quad (4)$$

$$N_{\nu_\mu} \simeq 3.6 \left(\frac{m_J}{\text{GeV}} \right)^{0.3}, \quad \bar{E}_{\nu_\mu} \simeq 0.04 \left(\frac{m_J}{\text{GeV}} \right)^{0.7} \text{ GeV}. \quad (5)$$

Note that the average ν_τ energy is significantly higher than the average ν_e and ν_μ energies, consistent with our remarks above. We derive similar $dN_{\nu_\tau}/dE_{\nu_\tau}$, N_{ν_τ} and \bar{E}_{ν_τ} parametrizations for the ν_τ generated by initial $t\bar{t}$ decay, $b\bar{b}$ decay, $\tau^+\tau^-$ decay, W^+W^- decay and decays which include extensions to the Standard Model (e.g. SUSY and Higgs sectors) in (MacGibbon et al., 2001).

In analogy with the use of the fragmentation function (1), we now apply (2), and its high energy extrapolation, to investigate the neutrino fluxes produced in astrophysical and cosmological scenarios.

3 Neutrino Fluxes from Astrophysical and Cosmological Sources

To calculate the expected ν_τ flux from a given astrophysical or cosmological source, the above ν_τ fragmentation function, Eq.(2), must be convolved with the initial distribution of the decaying particles, the Galactic or cosmological distribution of the sources and the redshift evolution and interactions of the emitted neutrinos as they propagate from source to Earth.

Here we briefly mention two scenarios. The new spectra for the tau neutrino fluxes expected from a number of other astrophysical and cosmological sources, including AGN and primordial black holes, are presented in our paper (MacGibbon et al., 2001).

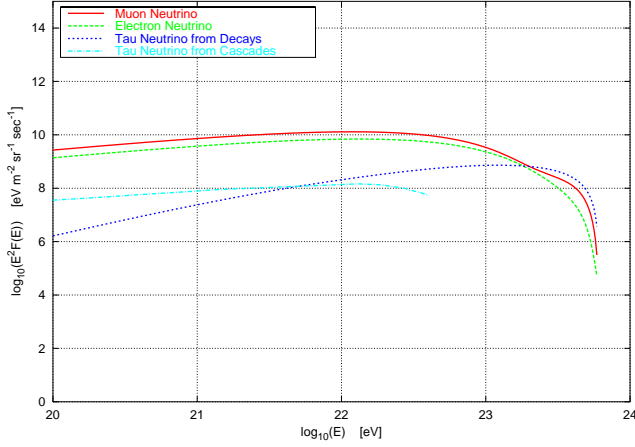


Fig. 3. The neutrino spectra from VHS cosmic strings with a mass per unit length of $G\mu = 10^{-8}$. The dash-dotted curve is the ν_τ component produced by cascades off the relic neutrino background (Yoshida et al., 1997).

Our first example is the VHS cosmic string scenario (Wichoski et al., 1998). However, our remarks apply generically to $p = 1$ cosmic string models. In the VHS scenario, 1 GeV - UHE particle fluxes are generated by the decay of supermassive scalar and gauge particles emitted by the long strings over the age of the Universe. The neutrino spectra expected at Earth from VHS strings with a mass per unit length of $G\mu = 10^{-8}$ are shown in Fig.(3) (Wichoski et al., 1998). The fraction of the ν_τ component which is solely produced in the collisions of the primary ν_e and ν_μ with the relic cosmic $1.9^\circ K$ neutrino background is represented by the dash-dotted line. (This is the only ν_τ component presented in previous cosmic string papers.) The dotted line represents the ν_τ directly produced in the hadronic decays of the string emission. As can be seen, our results give a significant increase in the expected ν_τ signal at the highest energies. Note too that because the cosmic ray background falls off as $E^{-\gamma}$, the highest energy region of the spectra is most relevant to detection. In Fig.(4), we show the neutrino spectra from a viable VHS model with $G\mu = 10^{-10}$ and the comparisons with present and proposed detector sensitivities.

As the second example, we briefly comment on the implications of our results for the simpzilla scenario. The annihilation of strongly interacting superheavy dark matter X particles captured by our Sun (simpzillas) has recently been explored as a source of observable ν_τ (Albuquerque et al., 2000). In this scenario the X particle decays into 2 quarks or 2 gluons which then decay into jets. Because of the high solar density, it is argued that only the $t \rightarrow W \rightarrow \nu$ chain in the X decay would produce a significant ν_τ flux capable of escaping the Sun. Assuming the fragmentation function (1) applies to the t quarks in this decay chain, the authors derive a distribution for the ν_τ produced per X particle decay which has a leading $E^{-3/2}$ slope above m_t . However, our full W^\pm decay simulations show that the ν_τ spectrum falls off with a much weaker slope, inconsistent with an $E^{-3/2}$

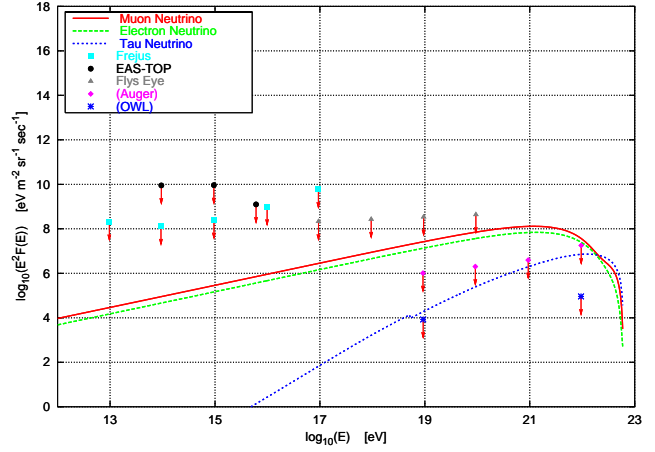


Fig. 4. The neutrino spectra from VHS cosmic strings with $G\mu = 10^{-10}$. Points with arrows represent upper limits for the flux (taken from (Bhattacharjee and Sigl, 2000)).

slope from the partial decay. As a resolution to this discrepancy, we believe that the application of Eq.(1) to the initial t distribution from X annihilation in the Sun is inappropriate because the short-lived t quarks are generated in the first step directly by the X annihilation, whereas Eq.(1) is a fit to the final state cluster distributions. Thus the appropriate distribution of the t quarks in this chain should be the initial distribution of the X particles times the relevant branching ratio. This skews the expected ν_τ distribution from solar X annihilation to higher energies. The modifications are discussed in detail in (MacGibbon et al., 2001).

4 Conclusions

Previous work has assumed that the ν_τ component in TeV - UHE hadronic decays is negligible compared with the ν_e and ν_μ components, at all neutrino energies. On examining QCD behaviour at accelerator energies and assuming similar behaviour continues to higher energies, we find this is not so. In particular, for neutrino energies in the decade below the energy of the decaying particle, the tau neutrino component is of similar magnitude to the ν_e and ν_μ components. Below these energies the ν_τ spectrum exhibits a slope of slightly less than $E^{-1/2}$ compared with the $E^{-3/2}$ slope of the ν_e and ν_μ spectra. This analysis modifies the expected spectra in many astrophysical and cosmological high energy neutrino production scenarios. As a consequence, the observation of a significant ν_τ to ν_μ ratio at a given energy in high energy neutrino telescopes and detectors may be due to hadronic decay at the source and not $\nu_\mu \rightarrow \nu_\tau$ oscillation in transit.

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